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The barriers to the progression of additive manufacture: Perspectives from UK industry

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ABSTRACT

Additive manufacture (AM) is receiving significant attention globally, reflected in the volume of research being carried out to support the commercialisation of the technology for industrial applications and the interest shown by government and policy makers in the technology. The lack of distinction between 3D printing and AM, as well as the portrayal of some highly publicised applications, may imply that the technology is now firmly established. However, this is not the case. The aim of this study is to identify the current barriers to the progression of AM for end-use products from an industrial perspective and to understand the nature of those barriers. Case study research has been conducted with organisations in the UK aerospace, automotive, defence, heavy machinery and medical device industries. Eighteen barriers are identified: education, cost, design, software, materials, traceability, machine constraints, in-process monitoring, mechanical properties, repeatability, scalability, validation, standards, quality, inspection, tolerances, finishing and sterilisation. Explanation building and logic models are used to generalise the findings. The results are discussed in the context of current academic research on AM. The outcomes of this study help to inform the frontiers of research in AM and how AM research agendas can be aligned with the requirements for industrial applications.

1. Introduction

The progression of additive manufacture (AM) has received international attention, with collaborative research, technology translation and commercialisation initiatives existing across the globe; America Makes in the USA (National Center for Defence Manufacturing and Machining, 2017), and High Value Manufacturing Catapults and the National Centre for Net Shape and Additive Manufacturing in the UK (Innovate UK, 2017; MTC Ltd, 2017). It is estimated that the UK has the potential to capture an annual £3.5 billion of the global economic market by 2025 (AM-UK Steering Group, 2017a). Although some technology leading companies have progressed their applications of AM under the scrutiny of the media, they do not form a true reflection of the technology readiness level of the technique across all industries. The reality is that the maturity and incidences of commercial AM products are highly specific to the industry, application, and company. In the past 5 years, multiple reports have been published by government and collaborative research and industrial initiatives to understand the economic importance, strategic and challenges associated with progressing AM in the UK and Europe (AM-UK Steering Group, 2015; AM-UK Steering Group, 2016; AM-UK Steering Group, 2017a; European Commission, 2014; European Technology Sub-platform in Additive Manufacturing, 2014; Innovate UK, 2015; Li et al., 2016a; Technology Strategy Board: Special Interest Group, 2012).

Comparably the amount of academic literature which addresses the challenges preventing the wider adoption of AM in industry, is extremely low, these are summarised in section 2. Ford and Despeisse (2016), present a case study analysis on the sustainability of AM in industry, drawn from open access information: company websites, news sources and academic publications. Niaki and Nonino (2017) and Dwivedi et al. (2017) implement direct consultation with industry into case study methodology to analyse the impact of AM on businesses in Italy and the USA, and India, respectively. More specifically in the UK, the AM-UK Steering Group (2017a) have recently presented the AM-UK National Strategy. This strategy includes ranked and brief summaries of the challenges facing industry, collected from workshops and online surveys consulting 123 organisations (AM-UK Steering Group, 2017a; AM-UK Steering Group, 2017c; AM-UK Steering Group, 2017d). To date, an academic study has yet to present an in-depth explanation on why

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industrial applications of AM have not progressed to more end-products in the UK economy.

This research aims to identify, from the perspective of UK industry, what the barriers to the progression of AM are, and why these barriers exist. This study answers these research questions using a case study approach and analytical generalisation of interviews with employees of 11 industrial organisations across the aerospace, automotive, defence and medical device industries. In addition this paper presents the industrial case study findings in contrast to the current status of research endeavours. The research satisfies a critical gap in the current knowledge presented by roadmaps and research literature. It identifies why the barriers exist, promotes a deeper understanding of the problems, and frames the difference between what is required by industry and what is currently active in research.

2. Additive manufacture

2.1. Overview of the technology

Additive manufacture is defined as the "process of joining material to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM International, 2015). Broadly, AM encompasses all additive techniques applied to all materials. The term 3D printing can be interchangeable with AM, particularly in the media. Within the research and industrial communities 3D printing tends to refer to polymer and non-enterprise based printing whereas AM is the expression used in a production-context. Rapid prototyping (RP) is often interchanged with 3D printing, however, it is generally applied to the manufacture of geometrically accurate models suitable for demonstrative, i.e. prototyping purposes. The accelerated development of 3D printing is demonstrated succinctly by the Gartner Hyper Cycle for Emerging Technologies (Gartner, 2017), progressing swiftly from technology trigger through to slope of enlightenment between 2010 and 2013, distinguishing between consumer and enterprise printing in 2014 and 2015 and progressing onto 4D printing (the 3D printing of components which are responsive to external stimuli over time (Khoo et al., 2015)) in 2017. The development of metallic, ceramic, polymeric, composite and biocompatible AM materials which are geometrically and mechanically functional have taken considerably longer to progress.

The industrial options for AM are constrained by the commercially available technologies. Metal AM falls into four categories: powder bed fusion, direct energy deposition, metal binder jetting and sheet lamination. The most promising technologies for the AM of structural parts are powder bed fusion and direct energy deposition. Powder bed fusion technologies selectively fuse feedstock on the build area using thermal energy (ISO/ASTM International, 2015). This technique encompasses selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM). The literature has investigated the application of SLS, SLM and EBM to medical devices (Cox et al., 2016; Hayashi et al., 2005; Shah et al., 2016; Traini et al., 2008; Wauthle et al., 2015) with increasing applications foreseen in the aerospace industry (Olakanmi et al., 2015; Uriondo et al., 2015). Direct energy deposition, uses a focussed thermal energy source to fuse materials as they are being deposited (ISO/ASTM International, 2015). This technique includes direct metal deposition (DMD) where the material is deposited in blown powder form and Wire and Arc AM (WAAM) where the feedstock is in wire form. Although deposition methods are well regarded for the potential impact they offer to industry (Frazier, 2014; Gu et al., 2012; Williams et al., 2016), to date research literature remains more focused on fundamental processing dependant parameters (Dinda et al., 2009; Ding et al., 2015a; Szost et al., 2016; Wang et al., 2015). Research literature reviews of AM predominately focus on a selected technology (Ding et al., 2015b; Flynn et al., 2016; Gu et al., 2012), a parameter within the process (Spears and Gold, 2016; Thompson et al., 2016; Yang and Zhao, 2015), a material (Gorsse et al., 2017; Mertens et al., 2017) or a certain application (Femmer et al., 2016; Guo and Leu, 2013; Li et al., 2015; Uriondo et al., 2015). An example of two broader reviews are those of Gao et al. (2015) and Gardan (2016).

2.2. Industrial implications

There are few academic publications focussed on the industrial implications of AM. Frazier (2014) presented a balanced review which incorporated both process, business and environmental considerations drawing on academic literature, industrial reports and conference presentations. Thomas (2016) discussed the economics of AM using a systematic break down of the supply chain and Huang et al. (2013) reviewed the impact of AM on society. Baumers et al. (2016) contextualised the economic implications resulting from an inter-process cost analysis between EBM and direct metal laser sintering. Schmidt et al. (2017) broached the impact of laser based AM on various industrial sectors. Gausemeier et al. (2011) conducted a selection of workshops with industrial and academic partners to identify current and potential applications of AM, and presented a matrix of success factors for the application of AM throughout a selection of industries. Pinkerton (2016) expanded on this data, with a brief explanation on the barriers to AM, however, the supporting literature is predominately research based as opposed to directly from consultation with industry.

Niaki and Nonino (2017) undertook a case study analysis of organisations in Italy and the USA, to assess the impact of AM on business competitiveness. Dwivedi et al. (2017) used an interview approach to derive the relationships and hierarchy between the barriers to AM in the Indian, automotive industry. Ford and Despeisse (2016) presented the opportunities and challenges of AM from industrial case studies extracted from company websites, news sources and academic publications. The portrayal of AM in the media is focussed on pioneering companies with high publicity products. Whilst the promotion of AM is crucial for industrial endorsement, encouraging collaboration, investment and public engagement, it can misrepresent the uptake, maturity level and magnitude of the sustainability benefits (Ford and Despeisse, 2016) of the technology across all industries and products. The reality is that the uptake of AM varies between types of industry (Pinkerton, 2016). This study confirms that a large amount of applications remain in the research and development phase (Ford and Despeisse, 2016), an observation which is supported by government initiatives aiding the translation of AM into industry (Innovate UK, 2017; MTC Ltd, 2017; National Center for Defence Manufacturing and Machining, 2017).

The most pertinent literature on the industrial implications of AM in the UK is The Additive Manufacturing UK National Strategy 2018–2025, which maps out strategies to overcome challenges in the following areas: cost/investment/financing, design, IP, protection and security, materials and processes, skills/education, standards and certification and test and validation (AM-UK Steering Group, 2017a). The strategy was proposed by the AM-UK Steering Group (2017b). The AM-UK Steering Group initially published a positioning paper (AM-UK Steering Group, 2015) and followed up by developing the National Strategy (AM-UK Steering Group, 2017a) in conjunction with industrial consultation. The methodology behind the industrial consultation is outlined in two update reports: data was collected via three workshops and also an online survey, gathering perspectives from 123 organisations across 15 industries (AM-UK Steering Group, 2017c), analysis of the data involved ranking and summarising the barriers (AM-UK Steering Group, 2017a; AM-UK Steering Group, 2017d).

3. Case study protocol

This research was designed as a multiple case study analysis. The unit of analysis was defined as engineering organisations, represented by an informed employee, and the geographical homogeneity was restricted to the UK. The inclusion and exclusion criteria are outlined in Table 1. These criteria allowed, informed participants to represent organisations

Table 1
Inclusion and exclusion criteria.

	Inclusion Criteria	Exclusion Criteria
Organisation	An engineering company	No involvement in design or manufacture
	Interacts with the UK economy	Location of manufacturing and/or design industry falls outside of the UK.
Participant	Employment in organisation	Not suitably qualified to give an informed opinion on design and manufacture (threshold employment status defined as graduate engineer)
	Gave consent to undertake study i.e. "willingness to participate"	During interview participant did not follow the framework of the interview

that design and/or manufacture, or facilitate manufacture of engineering products, within the UK. The original sample size was 12 case studies, based on the availability of resources. However during the course of the study analysis, the sample size had to be reduced to 11, due to one participant triggering the exclusion criteria.

Based on the author's interactions with and understanding of engineering organisations in the UK, and AM, a purposive sampling strategy was utilised, with a minimum quota of 2 organisations required to represent the industries and contexts represented in Tables 2 and 3. In addition, at least 2 organisations were required as case studies where AM had not yet impacted their end products. This strategy ensured a minimum number of case studies in each category which would yield rich, generalizable, believable information (Curtis et al., 2000). Once the minimum strategic sampling quota was met, a broader approach, recruiting companies across the entire sample population was used. Nevertheless the sample can-not be classed as a random representation of design and manufacturing industry across the UK, since the participants and organisations represent those "willing to participate" and must therefore be defined as a convenience sample (Robinson, 2014). The "willing to participate" criteria of the study, required by the ethical nature of dealing with human subjects, implicates an unavoidable bias into the study towards participants who, regardless of whether end-use AM is yet integrated into their organisation, had an opinion to express on the subject. As discussed in section 5, knowledge of AM is pocketed and fragmented, thus the criteria of "willingness to participate" created a bias towards participants who already had some experience of AM.

The organisations, referred to as the case studies, their involvement with industry and the engineering context in which they had considered AM within their businesses, are outlined in Tables 2 and 3 The engineering context highlights whether the organisations were manufacturing AM machines, end-use products, repairing parts, designing for AM or prototyping. Ethical approval was sought from the author's institution to conduct recruitment, interviews, analysis and publication of this research. The participants and their association with the case studies are identified in Table 2.

The case studies were assessed through interviews which took place between February and June of 2016. The structure of the interview was designed through an extensive literature review, the a-prior knowledge of the authors and a pilot case study report generated in consultation with an organisation interacting with the AM design framework across all engineering industries. The interview was designed with a semi-structured format, including open, probing and closed questions (Stanton et al., 2013). The interview was structured around five overhead themes: applications, design, Computer Aided Design (CAD), materials and manufacturing and post-processing. The interview is displayed in Appendix A, Table 5.

The interviews took place via telephone, Skype (Skype Communications SARL, Microsoft Corp., Luxembourg City, Luxembourg), or face to face format. The interview lengths are displayed in Table 2. The lengths of the interviews were constrained for two reasons. Firstly due to the availability of each participant, the interviews were scheduled with an hour time slot. Secondly the knowledge of a participant; in defining a representative sample across the industries and contexts listed in Tables 2 and 3, not all participants were able to reflect in detail upon all aspects of the interview. Since the interview was designed to identify the barriers to AM, where the participants had no experience in a certain area or perceived no issues in a certain area, the answers were shortened which, therefore, reduced the duration of the interview. In the majority of cases the interviewee had experience of one application aligned to one industry.

Coding of the case study interviews was undertaken using NVivo Plus (QSR International, Doncaster, Victoria 3108, Australia). The transcribed interview was coded against nodes in the following categories: industry (Table 2), context (Table 3) and the barriers to the application of AM to end-use parts (Table 4). Anonymous examples of the coding between the sources and the nodes identifying the barriers to the application of AM to end-use parts are given in Appendix B, Table 6.

Generalisation of the results was undertaken using analytical methods. The participants were informed representatives of the organisations, they were not indicative of all the knowledge and experience held by the company. Not all participants were able to reflect upon the entire spectrum of the interview, due to the specialised knowledge of the interviewees in particular industries and contexts. The issue of fragmented knowledge was raised by multiple participants and is expanded upon in section 5.1. Fig. 1, plots the percentage of organisations (of the sample size) engaged in AM in different engineering contexts, for each industry. Fig. 1 highlights both the imbalance between engineering contexts associated with the industrial areas and the small sample sizes. Of the 4 participants who were involved in the aerospace industry, all were conducting both design and manufacture of end-use products, only 75% used AM for prototyping and 25% also manufactured AM machines. In contrast, of the 2 participants who interacted with the heavy machinery industry, both were involved in the repair of existing parts and one manufactured AM machines, neither organisations were involved in design, prototyping or AM end-use products. The small sample sizes invalidate the use of statistical generalisation in this study.

Table 2
The industrial association of the case studies, the interview lengths and participants.

Case Study Sources	Industry Node					Interview	
	Aerospace	Automotive	Defence	Heavy Machinery	Medical Devices	Length (minutes)	Participant
1	0	0	1	0	0	36:48	1
2	0	1	0	0	0	22:39/26:01	2
3	0	1	0	0	0	31:21	3
4	1	1	1	0	1	54:39	4 and 5
5	1	1	1	0	0	43:39	6
6	0	0	0	0	1	49:20	7
7	1	1	1	0	0	47:06	8
8	0	0	0	1	0	26:58	9
9	0	0	0	1	0	32:25	10 and 11
10	0	0	0	0	1	12:10	12
11	1	0	1	0	0	55:27	13 and 14
Total	4	5	5	2	3		

Table 3
Engineering context of the case study organisations.

Case Study Sources	Engineering Context Node				
	Design	Prototyping	Manufacture of AM Machines	AM Repair of Existing Products	Manufacture of AM End-Use Parts
1	1	1	0	0	1
2	1	0	0	0	0
3	1	1	0	0	0
4	1	1	1	0	1
5	1	1	0	0	1
6	1	1	0	0	1
7	1	1	0	0	1
8	0	0	0	1	0
9	0	0	1	1	0
10	1	1	0	0	0
11	1	0	0	0	1
Total	9	7	2	2	6

Table 4
Coding of the case study sources to the barrier nodes.

Barrier Nodes	Case Study Sources											Total
	1	2	3	4	5	6	7	8	9	10	11	
Education	1	0	0	1	1	0	1	0	1	1	1	7
Cost	1	0	1	0	1	1	0	1	0	1	0	6
Design	1	0	0	1	1	0	1	0	0	0	1	5
Software	1	0	0	1	1	1	1	0	1	0	1	7
Materials	0	0	1	1	1	1	1	1	0	1	1	8
Traceability	0	0	0	1	1	0	0	0	0	0	0	2
Machine Constraints	0	1	1	0	0	1	0	1	0	1	0	5
In-Process Monitoring	0	0	0	1	1	0	1	0	1	0	0	4
Mechanical Properties	1	1	0	0	1	1	1	0	0	1	0	6
Repeatability	1	0	1	1	0	0	1	0	0	0	0	4
Scalability	0	0	1	0	0	1	0	0	0	0	0	2
Validation	1	1	0	0	1	0	0	1	1	1	1	7
Standards	0	0	0	1	1	0	0	0	1	0	0	3
Quality	0	0	0	1	0	0	0	0	1	0	0	2
Inspection	0	1	0	1	0	1	1	0	0	0	1	5
Tolerances	0	1	0	1	0	1	1	0	0	0	0	4
Finishing	0	1	1	1	1	0	1	0	0	1	1	7
Sterilisation	0	0	0	0	0	0	0	0	0	1	0	1

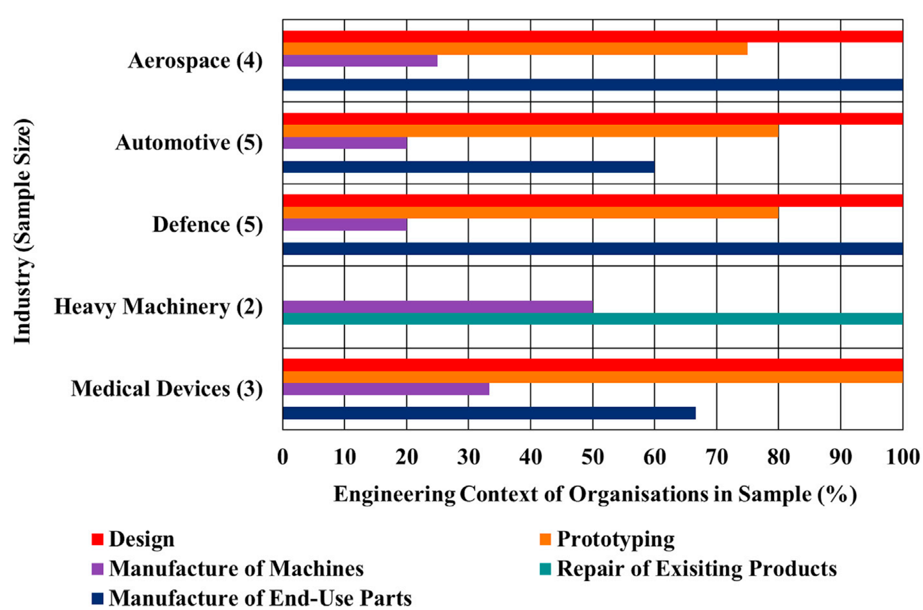

Fig. 1. Distribution of the engineering context of AM within the industry samples.

Analytical generalisation was undertaken using explanation building and logic models. Explanation building requires analysing the case study data to "explain" a phenomena (Yin, 2009). In section 5, the overhead barriers are grouped into standalone and overhead sections that expand upon the perceived barriers and contrast them to current academic research. Logic models are used to express causal theories over a chain of events (Yin, 2009, 2013). This research created logic models using the functional analysis framework taken from the theory of inventive problem solving (TRIZ) toolkit. TRIZ is a framework which guides systematic understanding and problem solving for engineering problems using past engineering and scientific knowledge (Gadd, 2011). In recent years TRIZ has seen an increase in its industrial and academic applications (Chang et al., 2016; Ilevbare et al., 2013; Russo et al., 2014). Functional analysis (Mindmanager, Mindjet, San Francisco, California, USA) taken from the TRIZ toolkit was applied to qualitatively demonstrate the physical interactions and knowledge propagation within powder bed fusion techniques (Gadd, 2011; Haines-Gadd, 2016).

A TRIZ functional analysis identifies problems with the functions of a system, by mapping the system into units of time (Gadd, 2011). Each defined component is a subject and/or object and the arrows between them represent an action from the subject onto the object (Fig. 2). The action is the influence causing change to the object, and is depicted by the aesthetics of the arrow, as depicted in Fig. 2, as either useful, useful yet insufficient or harmful. The full methodology behind functional analysis is fully outlined in Gadd (2011). The application of this methodology to results of the case study analysis is described through section 5.

4. Results

The coding of each case study source against the 18 nodes assigned to the barriers to the progression of the technology are shown in Table 4. Table 4, also includes the total number of sources (sample size of 11), which coded against each barrier node. The total number of sources coded to each barrier is displayed in Fig. 3. The most frequently identified barriers, above 50% of the total sample, were education, cost, software, materials, mechanical properties, validation and finishing.

With respect to the 7 most frequently identified barriers across all sources, Fig. 4 and Fig. 5 display the number of sources coded to these barrier nodes, for different industries and contexts. Due to the sample sizes and bias which exists across both the industries and contexts, statistical analysis is not possible, however these results indicate that some barriers may be aligned more strongly to certain industries and contexts. For

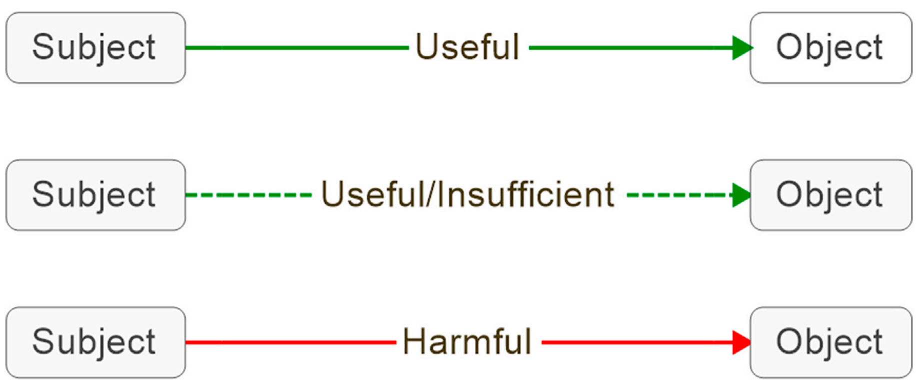

Fig. 2. TRIZ functional analysis example of methodology.

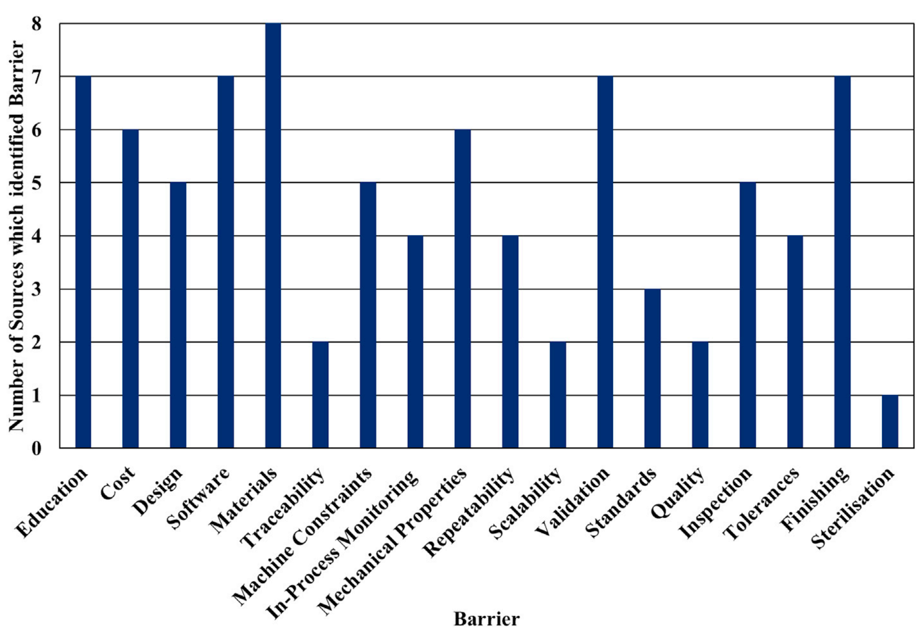

Fig. 3. Total number of sources coded to each barrier node.

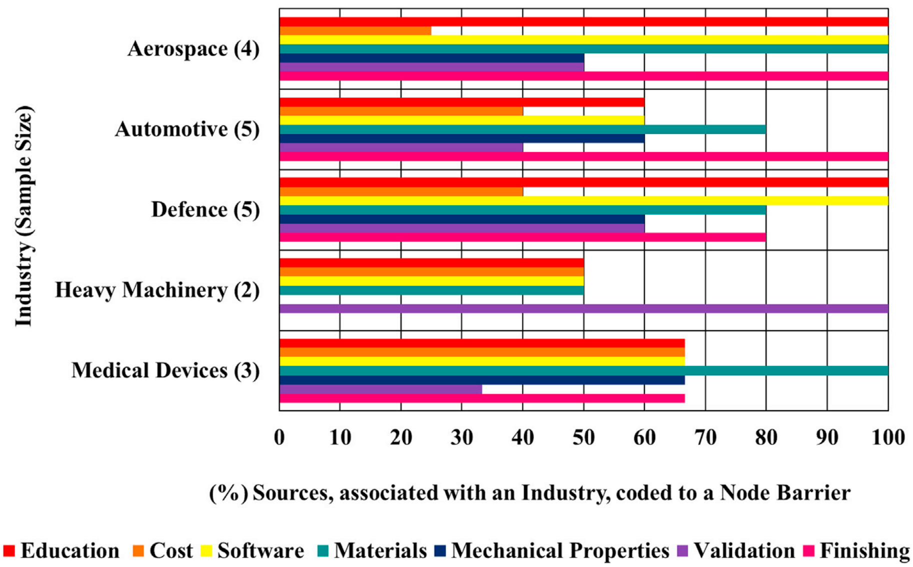

Fig. 4. Percentage of sources, associated with an industry, coded to a node barrier. Node barriers restricted to those who coded to above 50% of the total sample.

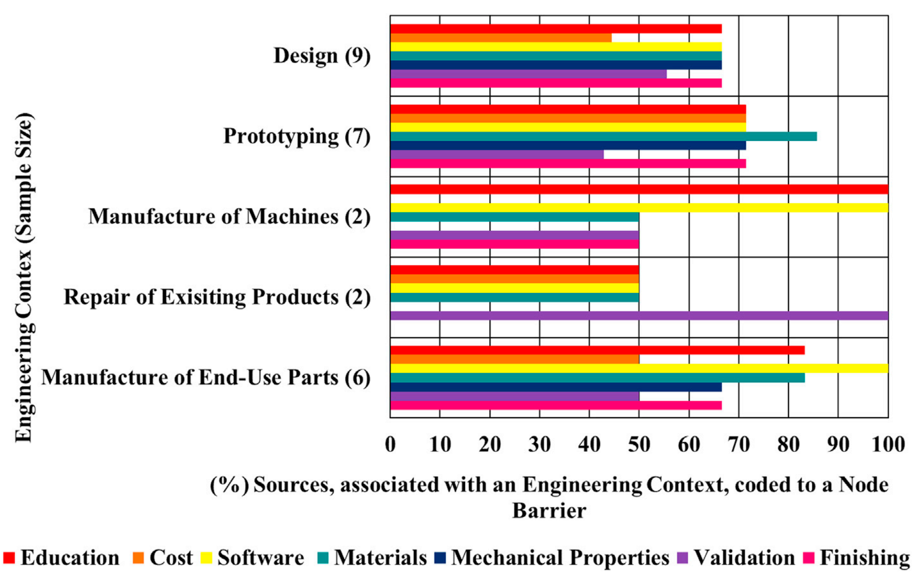

Fig. 5. Percentage of sources, associated with an engineering context, coded to a node barrier. Node barriers restricted to those who coded to above 50% of the total sample.

example, Fig. 4 shows that of the 5 participants from organisations in the automotive industry, 100% report finishing as a barrier, in contrast to the 2 participants involved in the heavy machinery industry who did not raise this issue. Fig. 5 shows that of the 7 companies using AM for prototyping, 71% viewed mechanical properties as a barrier, compared to the 2 organisations undertaking repair of existing products who did not voice this concern.

5. Discussion

5.1. Education

As discussed in section 3, during the interviews the participants focussed on their own knowledge and experiences of AM. Whilst the participants were informed representatives of their organisation, they did not represent the entire knowledge base held by the company. Knowledge of AM in industry exists in pockets; a point which was raised directly by some of the interviewees, very few people understand all the different methodologies. “The application of AM can be limited to whether the right people, with the right knowledge, are present in the appropriate project meeting” (Participant 1).

Some generalised courses exist to provide an overview of AM, or to teach compatible software techniques, however, these cannot deliver the required in-depth understanding over the full spectrum of AM techniques. Additive manufacture also has application dependent maturity levels; for many applications it is still in the research and development stage, consequently training cannot easily be outsourced. A barrier to knowledge transfer is the automated style of AM itself; the ‘black-box’ nature of the technology. “An analogy can be drawn with computer numeric control (CNC) machining” (Participant 1). Prior to CNC, a design engineer and technician would consult on the feasibility of a part for manufacture. With the paradigm shift towards automated manufacturing methods, the knowledge previously held by the skilled technician has

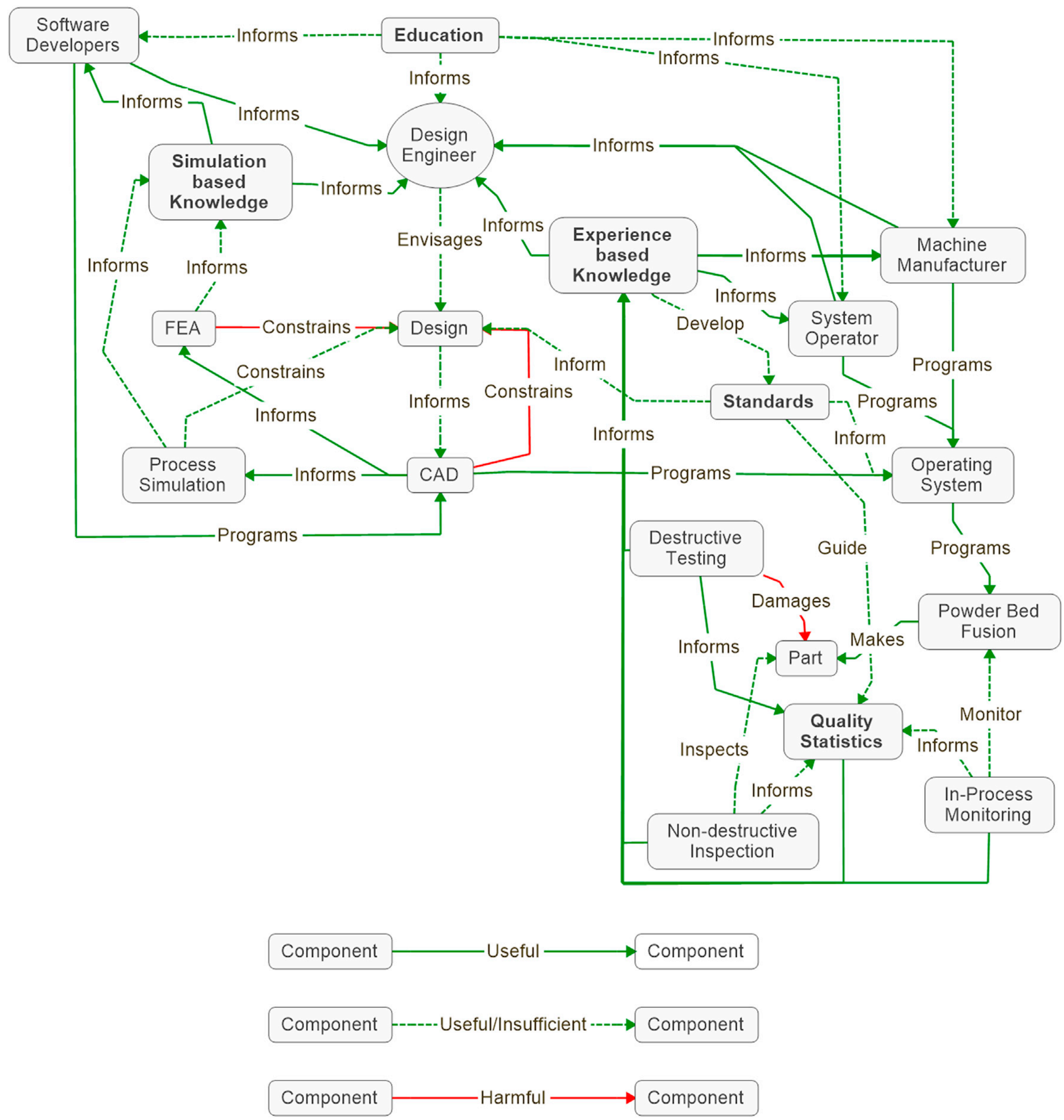

Fig. 6. Logic model demonstrating the propagation of knowledge in powder bed fusion.

been lost. This knowledge gap is particularly noted in graduates, who predominately only gain an overview of AM techniques, without an in-depth understanding or hands-on experience. The removal of this barrier requires paradigm shift in education.

Fig. 6 displays a logic model to represent the causal theory behind the limitations that impact knowledge interactions throughout powder bed fusion. It represents the fractured and inefficient propagation of knowledge. Education is a useful yet insufficient, informative action on the design engineer, software and manufacturing industries. Experience based knowledge, which draws upon the entire physical framework of AM including manufacture and testing, is feeding back useful informative knowledge to the design engineer. Similarly, simulation based knowledge, is gained from a multi-faceted interaction of software including CAD, finite element analysis (FEA) and process simulation. The limitations associated with software are discussed in section 5.4. Rather than a unified source of knowledge propagating through AM industry, knowledge is instead being propagated upwards fragmentally to engineers in design, software and machine manufacturing through practical and simulation based experience. This process results in an incomplete knowledge base. Research into education and teaching strategies in AM is extremely sparse. Huang et al. (2015) outline strategies for increasing AM knowledge in education, the workforce and public initiatives. The ADMIRE project is a collaboration between European universities and industry to develop a master's degree in metal additive manufacture (ADMIRE: knowledge alliance for additive manufacturing between industry and universities, 2017).

5.2. Cost

Fig. 7 displays a logic model to represent the causal theory behind the limitations that impact the physical interactions during powder bed fusion. The model describes how each physical component of the powder bed AM framework impacts upon each other, these interactions are often informative or constraining.

The aforementioned AM knowledge deficit is a cost consideration to any business, whether it can be filled by in-house training or on-the-job experience. All the physical process considerations shown in Fig. 7 also require equipment, consumables and changes to the supply chain. For a manufacturing technique with applications and processes still in the

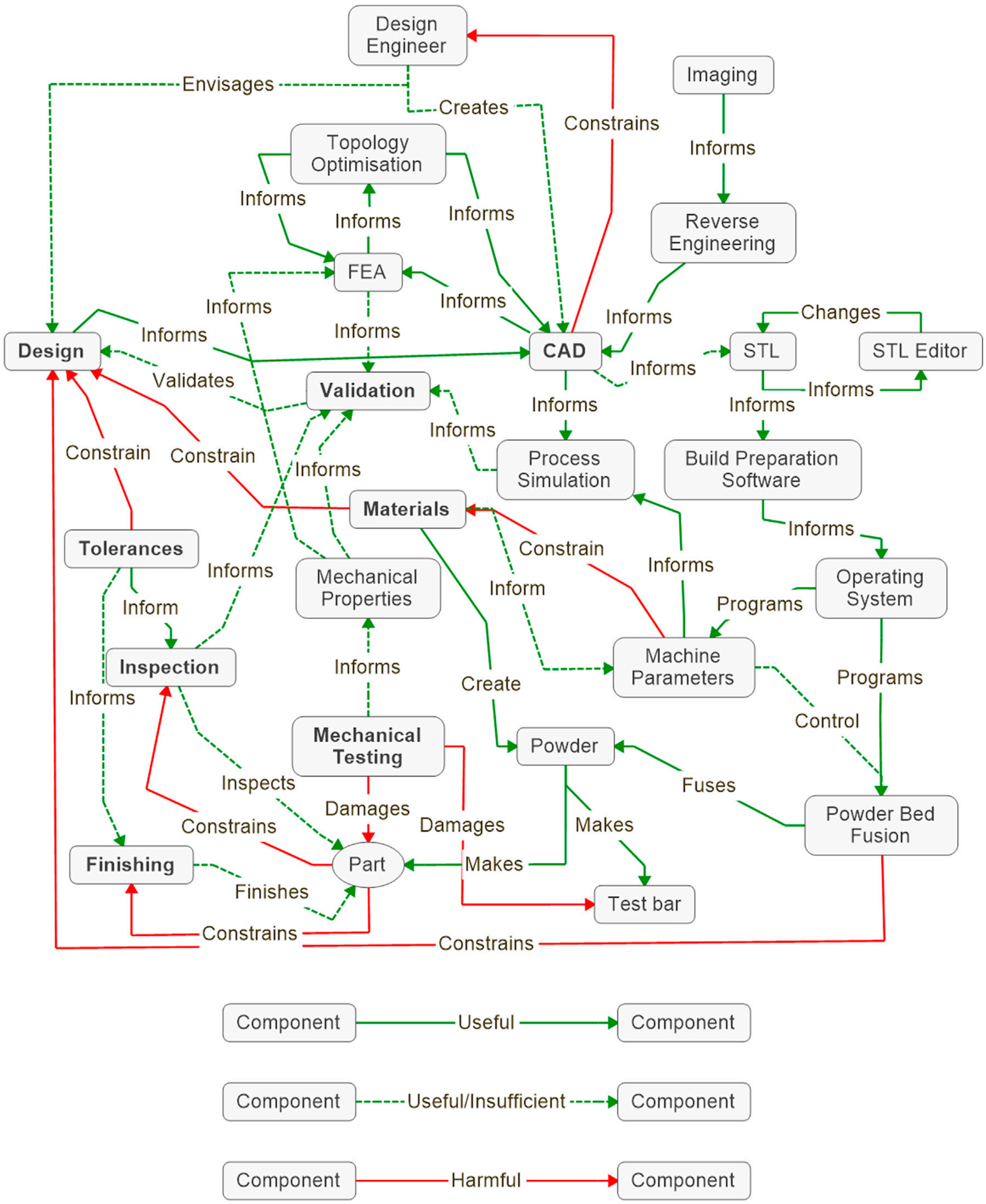

Fig. 7. Logic model demonstrating the physical interactions during powder bed fusion.

research and development stage, the outcome may be uncertain and, therefore, these cost implications become a business risk. The decision to pursue AM for a new part or redesign is generally approached using a business cost-benefit analysis. Do the savings associated with the different design and manufacturing method outweigh the upfront investment required in development, training and equipment?

During the interviews, the topic of cost was discussed in the context of the application. In industries where the product is high volume and low cost, the cost savings associated with changing the design and manufacture of a part do not warrant the expenditure required to facilitate this. In low volume and high cost parts, the long-term benefits seen by AM can more easily justify the initial expenditure. For example "the lower 'buy-to-fly' ratio offered by AM to the aerospace industry" (Participant 13). Cost-benefit analysis for AM is highly specific to the industry, in terms of the both application and production volume. Similarly to industry, universities also have to consider the costs and risks of implementing a relatively immature manufacturing techniques into the curriculum. However, with respect to section 5.1, as the industrial demand for graduates with experience in AM grows, so does the benefit of increased graduate employability.

In academic literature the cost implications of integrating AM into a business can be split broadly into either quantitative analysis of direct and indirect costs with respect to a case study part (Atzeni and Salmi, 2012; Baumers et al., 2016; Franchetti and Kress, 2017; Laureijs et al., 2017; Lei et al., 2016; Manogharan et al., 2016) or qualitatively including the wide-reaching implications of AM implementation on a company (Mellor et al., 2014). Ruffo et al. (2006) present a significant study in this field identifying the threshold number of parts to breakeven using SLS, for a given case study. An alternative perspective is offered by Piller et al. (2015) who discuss the impact of implementing AM beyond production cost and other firm level aspects, exploring the economic effects of AM as an "ecosystem" as opposed to at a single user level. Furthermore, Jiang et al. (2017) recently implemented the Delphi survey to predict future societal and economic implications of AM.

5.3. Design

Focussing on the design component of Fig. 7, the design engineer envisages the design, which is highly constrained by implications reflected from the manufacturing, materials and finishing. Therefore the interaction between design engineer and design is described as useful yet insufficient. The CAD software, discussed in depth in section 5.4, is simply a constraint to the design engineer. "The majority of the problems associated with AM can be removed or greatly alleviated by informed design for AM" (Participant 4). Yet, Design for AM (DfAM) is not routinely taught at undergraduate level. DfAM is a niche attribute, and an informed perspective can only be gained from *in situ* training, hands-on experience and a trial and error approach encompassing the entire design and manufacturing framework, i.e. all of the components in Fig. 7. Since this knowledge is not widespread, compared to conventional manufacture, it has effectively become a company's intellectual property and in many cases it is a highly protected asset. In addition to knowledge, DfAM requires creativity. "AM allows expanded geometric freedom, and rather than a manufacturing solution led design, you can approach the design from the point of view of the problem" (Participant 5).

DfAM is material, manufacture and manufacturing parameter specific; examples of these technique specific constraints on geometry can be found in the academic literature (Kranz et al., 2015). However, DfAM is a balance between understanding of the capabilities and constraints of the technique and the creativity required to problem solve with increased topology freedom. Very few studies have broached the concept of increasing creativity in the design framework (Doubrovski et al., 2012; Rosen, 2007). Topology optimisation software can idealise geometry for prescribed loads and boundary conditions and the resulting organic structures are often analogous with light weight structures that may be manufactured using AM. Research literature in this area has focussed on optimisation of certain aspects such as support and internal structures with reference to manufacturing constraints (Gardan and Schneider, 2015; Gaynor and Guest, 2016; Li et al., 2016c; Mirzendehdel and Suresh, 2016; Morgan et al., 2016). Ponche et al. (2014) demonstrate interesting work that begins to incorporate both design requirements and manufacturing specificities into an optimisation technique. However, these studies into automated design techniques are still heavily focussed on the constraints of manufacture rather than exploring the possibilities. The challenge for research is not to adapt for the constraints of AM but to formulate and explore new design spaces (Rosen, 2014).

5.4. Software

CAD is currently creating a bottleneck for expanding design and materials for AM. It revolves around the concept of extruding blocks and generating shapes through subtraction. Although for more traditional manufacturing methods, this methodology mirrors their subtractive nature, it opposes the additive nature of AM. In addition to the non-specialised nature of CAD for AM, current software is unable to efficiently exploit certain features that may be manufactured: graded materials using multi-jet printers or DMD, lattice generation and modelling porosity. Combining multiple software or add on packages can alleviate this limitation to a degree, for example, "regions of solid and porous structures may be integrated into the same component by merging a solid CAD model with point cloud data" (Participant 7).

Fig. 7 show the sheer number of interactions between CAD and other software: FEA, process simulation, image processing, STL editing, topology optimisation and build preparation software. "Software is fragmented; multiple tools, skills-sets and options with no standardisation" (Participant 6). Prior to build preparation, CAD geometry is converted into an STL format, after which it may be edited using an STL editor. Although it is a widely accepted file format for AM, "the STL format places a limit on the complexity of the geometry" (Participant 6). The STL neglects parametric data, represented as a useful but insufficient interaction in Fig. 7; therefore, if a build fails due to design features, the process must restart at the initial CAD model. In environments where the design and manufacture teams are remote from each other, this compounds the inefficiency. The need to incorporate design constraints into CAD and CAM software was discussed repeatedly during the interviews; "mitigating the 'black art of design' on a platform and software vendor level" (Participant 13).

Mirroring the situation in industry, the progression of software supporting DfAM in research literature is fragmented and targeted at isolated requirements. The software described by Vidimče et al. (2016) and Doubrovski et al. (2015) are significant developments in terms of compatibility for multi-material AM. Other recent advances in research include AM specific optimisation of topology (Gardan and Schneider, 2015; Mirzendehdel and Suresh, 2016), cellular structures (Sa et al., 2015) and manufacturing parameters (Morgan et al., 2016). However, these successes do not solve the overarching problem. To overcome the fragmented nature of software, a different perspective is required; a top-level approach must be taken drawing together the requirements of research and industry to create a streamlined design process across all software independent of application and platform. To this end, there is an industrially driven conversion from STL to the 3D Manufacturing Format (3MF) to ensure interoperability between software and retention of material and manufacturing specific parameters (3MF Consortium, 2017).

5.5. Materials

"The vast majority of the polymer components currently incorporated into our products are manufactured using materials which are not currently 3D printable" (Participant 3). The difference in the number of materials that are available for AM and those that may be conventionally manufactured is a huge barrier to its progression in end-use parts. This is represented in Fig. 7, by the constraints imposed on design by materials and on materials by machine parameters. If the material is not standardly available, then either a best match must be chosen, the part needs to be redesigned for an available material, or the material itself needs to be developed. "Along with the costs associated with DfAM, design considerations and techniques parameters vary between materials and impact performance" (Participant 4). Developing a new material for AM is costly, involving powder development, the quality control associated with the powder, and its compatibility with various AM techniques.

In an industrial context, constraining research to one material has been very successful. The development of titanium within the aerospace industry is a prime example, for which there is also a large body of academic literature to support (Akerfeldt et al., 2016; Promoppatum et al., 2017; Qiu et al., 2015b). "There is a focus on taking AM of Ti-6Al-4V through the technology readiness levels, systematically mapping out the control of the process. This includes informing supplier and internal engineers using powder specifications, to control the physical and chemical properties and technical specifications, to control the machine parameters, detection of defects and mechanical characterisation. Understanding the operational window for additively manufactured parts, speeds up the process of developing a concept through to an end-product" (Participant 13).

5.6. Machine constraints

All AM build chambers pose a limitation to manufacturability by the finite size of the bed platform and envelope. This constraint is accompanied by scalability issues, where sets of parts that vary in size can-not simply be scaled-up, the whole build platform must be redesigned. Size constraints are directly related to machine design and cost; as applications of AM become more widespread, manufacturers will naturally ramp up their scale to accommodate demand. Recent initiatives such as Big Area Additive Manufacture, demonstrates the manufacture of high performance thermoplastics which are unbounded in size (Li et al., 2016b). Another consideration of AM compared with other manufacturing techniques, is the relatively slow speed of the build cycle. This combined with cost considerations is a constraint when considering the progression of AM through to production of high volume, low cost products. A method to alleviate these issues is proposed by Wen et al. (2014) who detail the investigation of large scale and multi-laser beam SLS.

The automated nature of AM imposes constraints, not just in terms of knowledge transfer (section 5.1), but the finite build time, during which the geometry cannot be adjusted. This highlights the value of informed and accurate DfAM and validation. Comprehensive design knowledge, manufacturing and material constrains integrated into CAD, and process simulation could detect and avoid a build failure prior to manufacture. Whilst in-process monitoring can detect build failure and alert the operator, identifying an error in the design during the build is still hugely inefficient in terms of time and cost.

5.7. Quality

Quality control encompasses in-process monitoring, traceability and standards; it is the overarching term to ensure that the parameters within the process statistically fall within a confidence interval. Fig. 6 shows that quality is currently informed by useful but insufficient data from in-process monitoring and inspection. At this moment in time, quality control is predominately dictated by in-house documentation specific to the industry, application, manufacturer, material and manufacturing method. There is a well acknowledged deficit in the number of standards governing AM processes. Fig. 6 shows how insufficient standards information impacts design, operating systems and quality statistics. The deficit in AM standards has only recently begun to be rectified (ASTM International, 2017; Seifi et al., 2017).

"The uniqueness of AM lies in the fact that material is being made as opposed to just manufacturing a shape" (Participant 4). This makes quality control and traceability difficult. Parameter variation within the build has a direct effect on the quality of the material; laser power and layer thickness in SLM have been shown to change the stability of the melt flow and hence the material porosity and surface roughness (Qiu et al., 2015a). The current aim of in-process monitoring, applied to metal powder techniques, is to feedback on the quality of the melt pool and part geometry. "For the DMD process, additional processes require monitoring, for example, bead height and powder flow" (Participant 10). Processing parameters have been shown to influence the microstructure, geometric structure and mechanical properties of direct laser deposition structures (Qiu et al., 2015b). "Machine manufacturers recognise that in-process monitoring is a key area for development" (Participant 10). "In simple terms, a layer by layer green-red light system is required indicating, good powder, good spread and good fusion with no defects" (Participant 8). In turn, informative and accurate in-process monitoring, will lead to robust quality statistics.

The PrintRite3D® technology (Sigma Labs Inc., Santa Fe, New Mexico, USA) gives an example of the current industrial standard. Optical monitoring detects deviations of the geometry of the build from a reference 'gold standard' image, up to a resolution of 100 μm in-plane (Sigma Labs, 2017). Changes in the temperature of the melt pool are detected from a change in the emissivity. Advances in research have explored alternative imaging techniques including optical coherence tomography for surface characterisation (Guan et al., 2016) and low-coherence interferometric imaging for melt pool morphology (Kanko et al., 2016). Zhao et al. (2017) present *in situ* monitoring of the physical processes during powder bed fusion using high-speed x-ray imaging. The long-term requirements of industry and aims of research are to create a closed-loop system (Spears and Gold, 2016), where the process parameters are controlled by the feedback, thus allowing for in-build compensation of fluctuations as they occur.

Quality control of powder requires quantification of the properties, across suppliers and batches. Whilst recyclability, is "a fundamental component of the economic argument for AM" (Participant 8), the reuse of used metal powder in AM has an impact on traceability. The requirement for robust quality statistics is undermined by difficulties in traceability of powder, insufficient in-process monitoring, fractured design and software frameworks, and repeatability issues in terms of mechanical properties (discussed in section 5.8). Using Ti-6Al-4V in aerospace again as an example, by narrowing the material, platforms and application window, issues with quality can begin to be resolved through statistically defining operational windows for each design variable. Essentially a controlled route to production enables reproducibility.

5.8. Validation

AM processing conditions have a huge effect on material microstructure and the mechanical properties (Qiu et al., 2015b, 2015c). Where mechanical properties are quantified, they are repeatable for a fixed machine, material, geometry and a series of build parameters. Even where build parameters are fixed, there are still uncertainties within the build that create variations in the formation of the material, hence, the requirement for in-process monitoring and repeatability quantification. Thermal stresses in powder bed fusion and direct energy deposition techniques are a significant issue that can lead to distortion of the part, fixture supports peeling off the part and in extreme cases the substrate platform bending. Methods required to alleviate part distortion vary between design, material and AM platforms, due to the variation in thermal interactions with the material, volume and fusion method. "Reducing volume in geometry at the design stage can reduce distortion by minimising heat input into the part" (Participant 4). "Where residual stresses cannot be mitigated in the design process, they can be alleviated using support structures followed by heat treatment" (Participant 6).

Thermal stresses can also be mitigated at the design stage by an awareness of potential deformation using simulations of the thermomechanical build process. Simulation software such as Netfabb® (Autodesk, San Rafael, California, USA) can thermomechanically simulate metal AM builds to predict the build-up of thermal stresses. Process simulation is a powerful tool as it can allow a designer to redesign to remove residual stress or compensate for deformation within the design. Thermomechanical simulations are computationally intensive and time consuming. "They are currently so complicated that it will be a while before it can be integrated with FEA" (Participant 5). However, long build times that may fail through distortion are also inefficient in terms of time and cost. "Alternatively, in-process thermal monitoring has the potential to avoid the build-up of thermal stresses by closed loop control of contributing build parameters; toolpath, laser power and substrate temperature" (Participant 10).

In the context of DfAM, ideally, process simulation would allow for optimisation of a fixed or adaptable process parameter for a given mechanical variable. Whilst research has made significant strides in simulating factors such as the effect of processing parameters on the thermal and phase change behaviour of the melt pool (Shi et al., 2016), thermal stress and distortion (Cao et al., 2016) and grain growth (Lopez-Botello et al., 2017), these advances have yet to be integrated parametrically with a DfAM interface.

The complications surrounding variable parameters during AM process and the impact on the material directly influences the ability to validate AM using FEA. In industry, the most common method of statistically quantifying the mechanical properties is via material equivalence or extracts from the part and destructive testing. The participants gave a variety of responses to the issue of mechanical characterisation. Essentially test bars "may not capture variation in grain growth across the build" (Participant 6) and also "add cost to the process" (Participant 1), providing both a limited representation and additional costs considerations. However, alternative positive views were also given; "focussing on the robust mechanical characterisation of a material, gives a statistical distribution insensitive to the AM machine" (Participant 13), allowing repeatability for process parameters through an operational window. The summary of the relationships between these factors is shown in Fig. 7, via a series of useful yet insufficient interactions with the validation component.

5.9. Finishing

Resolution between AM machines vary, and as a stand-alone technique it generally requires some form of surface post-processing. "Powder bed metal AM does not create defined edges; variation between 100% density and 100% air results in partial fusion with adherence of half formed particles" (Participant 8). The interviews raised two major aims for surface finishing techniques, either to achieve a dimensional tolerance or a surface texture. For automotive applications; "surface cleanliness and submicron tolerances are a key concern" (Participant 2). Medical applications require cleanliness and must be sterile; "porous fixation on surfaces are particularly challenging where interconnectivity exists" (Participant 12). Surface finishing difficulties are represented in Fig. 7 through a series of insufficient and harmful interactions between the part, finishing, inspection and tolerances. These issues, also follow through to impact the design and validation components.

Design and manufacturing parameters affect surface finish: laser power, exposure time and orientation (Krol and Tanski, 2016; Qiu et al., 2015a) and in turn surface finish can affect the mechanical properties (Everhart et al., 2016). The impact of processing parameters on surface finish has also begun to be investigated using thermomechanical simulation (Lee and Farson, 2016). Options for surface finishing of AM parts described in research literature include mechanical blasting, chemical etching, electro polishing, laser ablation, micro-machining and vibratory grinding (Bagehorn et al., 2017; Lhuissier et al., 2016; Longhitano et al., 2015; Mohammad et al., 2016; Wang et al., 2016). For internal features, such as lattices, the inability to finish the surfaces is a huge barrier to their progressive use. At present, options for internal surface finishing in industry are in the research phase and hence are commercially sensitive.

As a technique in isolation, the phased nature of the surfaces achieved by AM makes achieving a dimensional tolerance difficult. Machining techniques can remove half formed particles, and tolerances can be achieved, but only in reference to a known datum. Post build the only certain datum surface is adjacent to the build platform. In addition, the often organic and thin walled nature of AM parts can make them flexible and the thermal nature of the techniques can cause deformation through residual stress. Of course, for non-machine based surface finishing techniques, which are often used for internal surfaces, it is even more difficult to achieve a uniform, quantifiable tolerance.

The line-of-sight difficulties faced by surface finishing of internal features are similar to those for inspection methods. In addition, inspection needs to be able to quantify internal porosity and the presence of loose powder. A recent study has highlighted that no single measurement technique can reliably replicate topographic features (Senin et al., 2017). Similarly to the quantification of mechanical properties, internal surface dimensions, texture and porosity can be measured using destructive techniques to develop a statistical operating window (Romano et al., 2017).

5.10. Summary

Eighteen barriers were extracted through case study interviews with representatives of 11 industrial companies across the aerospace, automotive, defence, heavy machinery and biomedical industries. Analytical generalisation was utilised to summarise the issues faced by the participants, of which education, cost, software, materials, mechanical properties, validation and finishing occurred in 7 or more interviews demonstrated by Fig. 3. The findings of this study align well with the UK National Strategy (AM-UK Steering Group, 2017a). Although the methodology and analysis of results in this study are inherently different, of the 7 thematic workgroups on which the UK National Strategy is based, 6 are mirrored in this research. This strengthens the external validity of the study.

The results displayed in this research are not a statistical representation of the limitations of AM across all UK industries. They are highly reflective of the participants "willingness to participate" creating a bias, in terms of the engineering context (Fig. 1). In addition, the participants themselves represent a proportion of the knowledge held by the organisation they represented. Though applications in this study were not explicitly discussed, there was an also notable omissions in terms of discussion of WAAM techniques. This created a bias in the study towards metal powder AM.

To gain a detailed, informative perspective, an interview approach was required, which in turn required time commitment and associated staff costs from the companies involved, hence restricting the representation of the analysis. However, as discussed in section 5.2 knowledge of AM in industry is not only held by specific people but tends to be highly specialised in terms of techniques and applications. Figs. 4 and 5 show a higher frequency of coding between certain barriers and different industries and engineering contexts. Due to the sample size and inherent bias created by the "willingness to participate" it is not known whether this is true reflection between perceived barriers and industries and context. However, the AM-UK Steering Group (2017a; 2017d), raise similar observations in their analysis. This interpretation creates an opportunity for further research to establish whether certain barriers are more strongly aligned with different industries and engineering contexts. In doing so, there is the potential to economically target industrial and engineering context specific development strategies.

The quality of case study research design can be judged against four tests; construct validity, internal validity, external validity and reliability (Yin, 2009). Construct validity in this study was ensured by multiple units of analysis and a chain of evidence, described in section 3, incorporating the sampling strategy, interview development and structure (Appendix A), utilisation of qualitative software, coding examples (Appendix B) and analytical generalisation methodology. The internal validity of case study research involves assessing the accuracy of the inference (Yin, 2009). The internal validity, based on the parameters of the case study protocol, was demonstrated between explanation building and logic models. The external validity has been established against the recently published UK National Strategy for AM (AM-UK Steering Group, 2017a). The reliability of the study can be confirmed by the case study protocol, outlined in section 3.

6. Conclusions

This study presents an in-depth assessment of the barriers to the progression of AM as perceived by industry. It also highlights where there is a mismatch between the aims of recent strives in research compared to the limitations faced in industry. In doing so, it offers a roadmap to the future where the endeavours of research are drawn more closely in line with the requirements of industry. "AM is a tremendous opportunity, but it requires engineers to develop a set of skills to support it, processes are required before and after; that is the biggest hurdle for the adoption of AM" (Participant 8).

This research has drawn the following conclusions:

- Knowledge of AM held by current engineering graduates is insufficient. In industry, this problem is exacerbated because knowledge is rarely unified and comprehensive, instead it exists in pockets which is highly dependent on personal experience. This barrier requires a paradigm shift in education to satisfy the need for graduates with deeper understanding and experience of AM.
- Cost-benefit analysis is highly application specific and incorporates an element of uncertainty, compounded by the lack of well-rounded AM knowledge filtering into industry.
- DfAM necessitates that designers have a new perspective, requiring increased creativity, underpinned by AM specific knowledge and experience.

- Software for AM is currently severely fragmented in industry and research. The process requires streamlining through the design, optimisation and build preparation processes to create software that is tailored to DfAM yet platform independent.
- The lack of materials available for AM either inhibits the manufacture of certain parts or requires them to be redesigned for different materials. Industrial application requires a parameter dependent operational window for materials to speed up the translation of concept through the end product.
- Bed size and the speed of AM are limitations for mass manufacture.
- In-process monitoring systems are crucial to ensuring good quality statistics. In the long-term, industry requires closed loop systems which compensate for in-build fluctuations.
- Quality control is predominately dictated by in-house specifications and requires more guidance from overarching standards. FEA can no longer support the validation of designs for AM, where the mechanical properties are highly dependent on the processing parameters. Thermomechanical modelling can aid design, but it is time and computationally intensive. Currently the most robust method of statistically quantifying the mechanical properties, in the presence of uncertainties in the build process, is material equivalence.
- Line of sight difficulties for inspection and finishing are a key focus in both research and industry. Where internal features can be finished by mechanical, magnetic, electrical or chemical techniques, surface quality quantification is still limited by deficiencies in imaging resolution.

Conflicts of interest

There are no personal or financial conflicts of interest associated with this study.

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Appendix A

Table 5
Interview questions.

Area	Open	Probe	Closed
Applications	How is additive manufacturing (AM) utilised in your company or by your customers?	What applications has AM been applied to within your company?	Were these applications for prototyping or end product manufacture or both?
	Do you design for and or/manufacture AM parts?	What type of AM has been utilised by your company or customers?	What benefits does AM bring to your products, customers and company?
			What limitations are preventing the various methods of AM being applied to more applications in your field?
		What standards or certification is required for design and manufacture in your field?	Are these compatible with AM? If not why not?
		Do you have IP issues relating to the customisation of AM parts?	Do you foresee any future problems with IP?
	What are your personal experiences with AM?	What applications have you applied it to?	What do you feel were the main advantages of using AM in these instances?
			Did you encounter any problems applying AM?
Design	Do your design methods differ between AM fabricated parts and traditional manufacturing methods?	If so, what design techniques do you use for AM fabricated parts?	Do you feel that you are able to optimise a design for AM using these methods?
		If not, why not?	Do you feel that AM is fully optimised using traditional design methods?
		Do you factor build orientation and surface finish considerations into your design?	Can you obtain tolerances sufficient for your application?
	Does your background knowledge of AM and materials influence how you design products?	Do you and your designers have a good working knowledge of AM and all the different techniques available?	If so, how do you keep your design team up to date with current developments in the area?
			If not, do you feel that this could enhance how you design AM products?
		Do you feel that alternative design techniques would alleviate any of these issues?	Do you think that the time and cost associated with retraining designers in the short term, would be worth the longer term goal of exploiting AM more effectively?
CAD	What experience do you have of using CAD to create models for direct AM fabrication?	Do your design techniques combine your CAD software and AM efficiently?	Do you think that there is scope to improve design and CAD methodology to utilise AM fabrication more efficiently?
			What CAD/CAM software do you use?
	Do you notice a difference in how well CAD deals with AM parts as opposed to traditionally manufacture parts?	Do you encounter any problems using current CAD software, when designing AM parts?	Have you encountered memory usage limitations?
			Do you use any additional packages with your software, specifically for AM?
			Do you experience problems converting your CAD files to AM compatible STL files?
			Do you experience trouble editing AM parts?
		How do you feel CAD could be improved to ease design of AM parts?	Would additional functionality to the current software be acceptable? Or would an entirely new approach to CAD modelling be preferred?

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Table 5 (*continued*)

Area	Open	Probe	Closed
Materials and Manufacturing	What materials do you use or design with for AM manufacture?	Are there limitations in the choice of materials for AM?	Do suppliers give a good range of mechanical properties for AM materials?
			Do materials vary between batches or suppliers?
		Are these materials recyclable?	Does this create any issues in the lifecycle of the product?
		What quality control steps do you have for AM materials?	Do you conduct your own quality tests on supplied AM materials?
	What end products have you designed for or manufactured using AM?	What benefits and problems have you seen in the use of AM for end products?	What developments to the technique would overcome the issues?
		What quality control steps do you have during the AM process?	What issues do you have with repeatability? Are these influenced by platform position, material, machine, build style orientation?
		Do you do additional mechanical testing on AM fabricated parts?	If so what? Strength, fatigue, wear?
Post-processing	What post-processing methods to you apply to your AM parts?	How do you finish surfaces?	Do you have any issues with powder fixation? Can you overcome these?
		Do you have any problems with thermal stresses?	How do you relieve these?
			Do you foresee scalability problems with thermal stresses in larger metal parts?
			Do you conduct additional heat treatments to tailor the mechanical properties?
Miscellaneous	Do you use AM for parts that require regular inspection?	Do you have any issues with AM and parts that require regular inspection?	Do you conduct non-destructive testing on the parts?
	Do you foresee an increased use of AM for end product manufacture?	If so, why?	Would development of the technique and hence increased use of AM for end stage products have a positive effect on your business? How?
		If not, why not?	What do you see as the major limitations of AM preventing its widespread usage in end-stage product manufacture?
	Are the any further observations that you would to add on this subject that has not be covered by this interview?		

Appendix B

Table 6
Examples of coding between case study sources and nodes representing the barriers to the application of AM to end-use parts.

Barrier Nodes	Example of the Coding between Case Study Sources and Barrier Nodes	Case Study	Participant
Education	"The informed decision is in people's heads, so you are having to invest the knowledge in people's heads about the different approaches, before you can make a decision about what you are going to do."	1	1
Cost	"The big one is probably cost, at the minute, I think as time goes by that will go down."	8	9
Design	"Those design rules don't exist yet, now they are one of the blockers, because effectively what you want to be able to say is, this is how we design it, this is how we certify it, but if it requires you to go all the way through the design process, in order to validate the performance, and we know the repeatability is a problem, because properties changes across batches, then that presents as a business problem."	1	1
Software	"Current CAD packages are prohibitive for designing things for additive, you know, the embedded function within the CAD packages are built on cutting methods, you extrude, you chamfer, you fillet."	4	4
Materials	"Materials are expensive and materials are limited."	3	3
Traceability	"Traceability is a problem." "Even if we produce the report that says: the powder does not degrade, you can use it forever. Are aerospace going to accept that? It just doesn't look, smell or feel right to have multiple powders going on forever and a day."	4	4
Machine Constraints	"Generally, printer to point, what I mean is, there is a laser or extrusion head, or maybe a more conventional print head, but generally I am curing material or laying down material, in a small amount per unit time, this means the processes are relatively slow."	3	3
In-Process Monitoring	"Certainly in-process monitoring is a key area that all AM manufacturers recognise as a need."	9	10
Mechanical Properties	"ALM (additive layer manufacture) would not have the fatigue strength"	6	7
Repeatability	"The confidence isn't there, in the repeatability of powder, between batches and suppliers."	4	4
Scalability	"You can't scale the whole build, you have to go back to native file and scale that first."	6	7
Validation	"The thermal analysis, from a layer by layer, brick by brick, element by element model in terms of looking at the formation of thermal stress, they are incredibly computational dense, they take vast amounts of processing power in order to simulate these things."	11	13
Standards	"The standards for additive manufacturing are currently being generated, they just don't exist."	9	10
Quality	"I don't want to be alarmist, and it is hard to put numbers on it but yes, the confidence is not there, in the repeatability of powder from batches and suppliers. And their supply, how are they atomised in the first place? The methods used are different, or can be different, should I say."	4	4
Inspection	"The concern would be having to add additional inspection, because of any additional lattices and cavities you are creating because of 3D printing."	2	2
Tolerances	"You take a component like that (indicates example of component), because it is very organic, it is difficult to hold, so getting it into the machine to hold it is hard, once you have got it into the machine it is very flexible, so, you know as you start to machine it moves around and it's flexible because it is made of AM and because we have made it very lightweight, so suddenly it gets quite difficult to machine it. It also turns out that, we perhaps only need to do machining in these areas and these areas, but because of the	7	8

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Table 6 (*continued*)

Barrier Nodes	Example of the Coding between Case Study Sources and Barrier Nodes	Case Study	Participant
	way AM builds because of the distortion that goes on, you don't know precisely where those features are, so it is actually quite difficult to find them on a conventional machine tool."		
Finishing	"Well I guess it is the manual pro-processing of metal parts, it is non-automatable, the removal of supports and fettaling."	5	6
Sterilisation	"Limitations on ALM really, for medical companies, are cleaning, that is in essence getting out the powder, the unfused powder, and secondly making sure it is sterile."	10	12

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